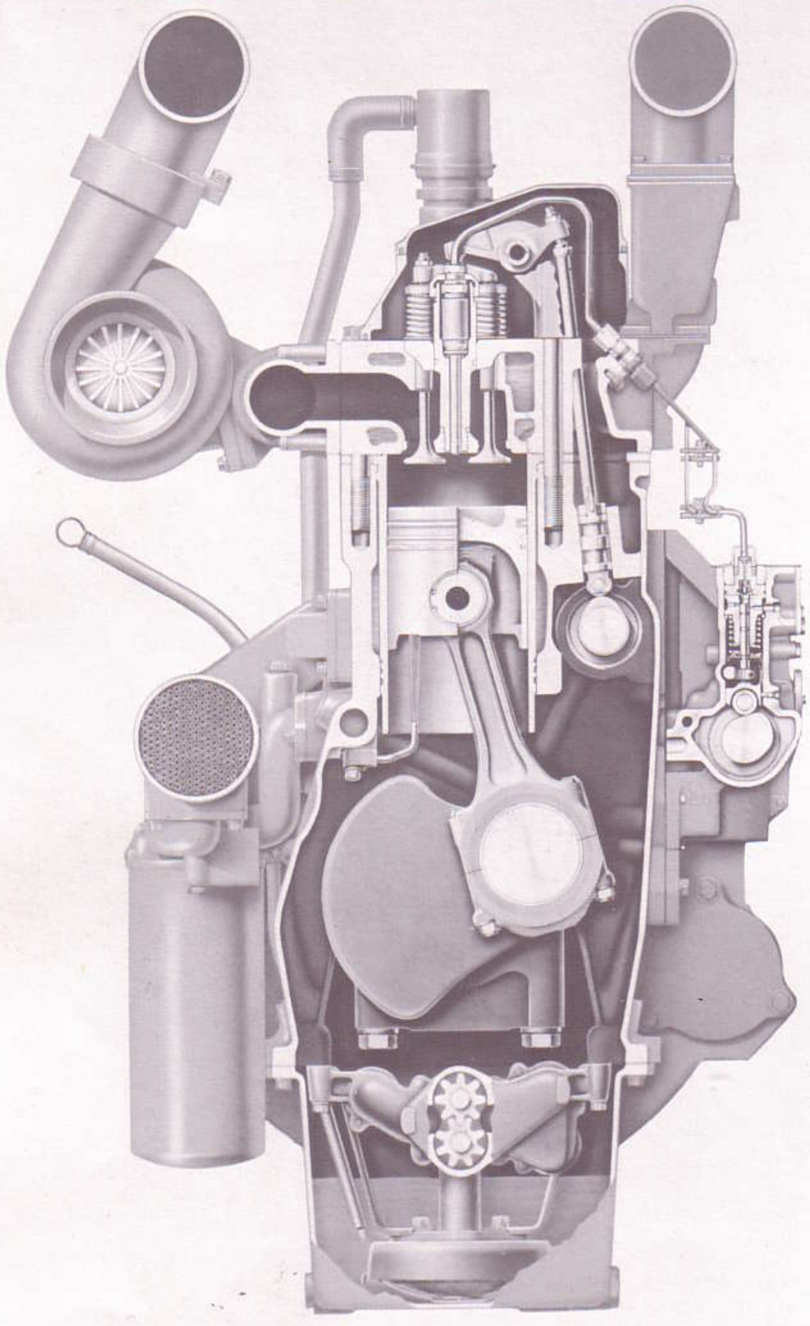
product support
bulletin

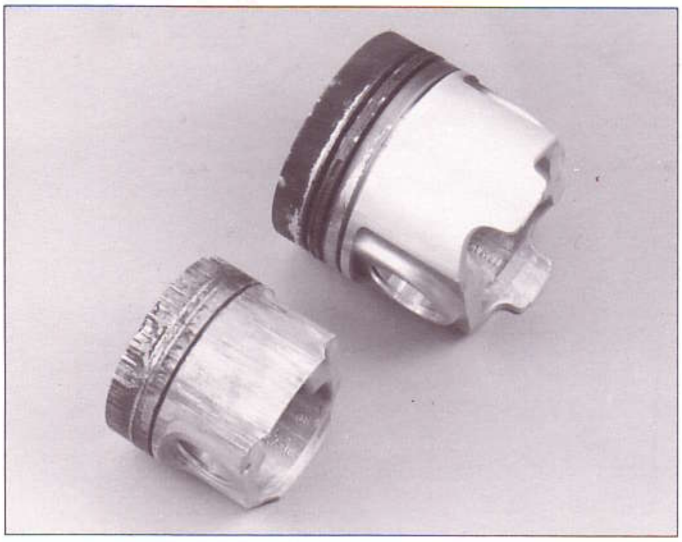
How Diesel Engines Work and Wear



Engine Systems

- Cooling
- Lubrication
- Fuel
- Air Intake & Exhaust
- Electrical

This bulletin gives an overview of diesel engines, how they work and typically wear, plus the common warning signs of engine problems. The objective is to give you a thorough understanding of engines and help you effectively market Caterpillar® products and your dealership's Engine Repair Options.

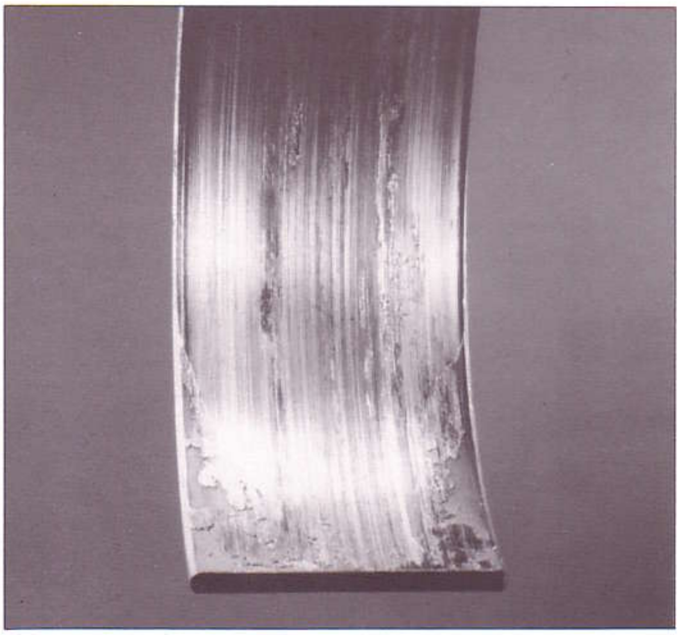


Piston with normal wear on right, abnormal wear on left.

Engine Wear

Hand in hand with the discussion of how engines work is how they wear. For our purpose, we will classify engine wear into two categories; normal and abnormal engine wear.

Normal wear occurs in all engines. As parts push, slide and work against each other, wear occurs. Normal wear is that which we expect during engine operation. The normal wear items in a diesel engine include the piston rings, cylinder liners, valves and valve guides, main and rod bearings and if equipped, turbocharger bearings and seals.

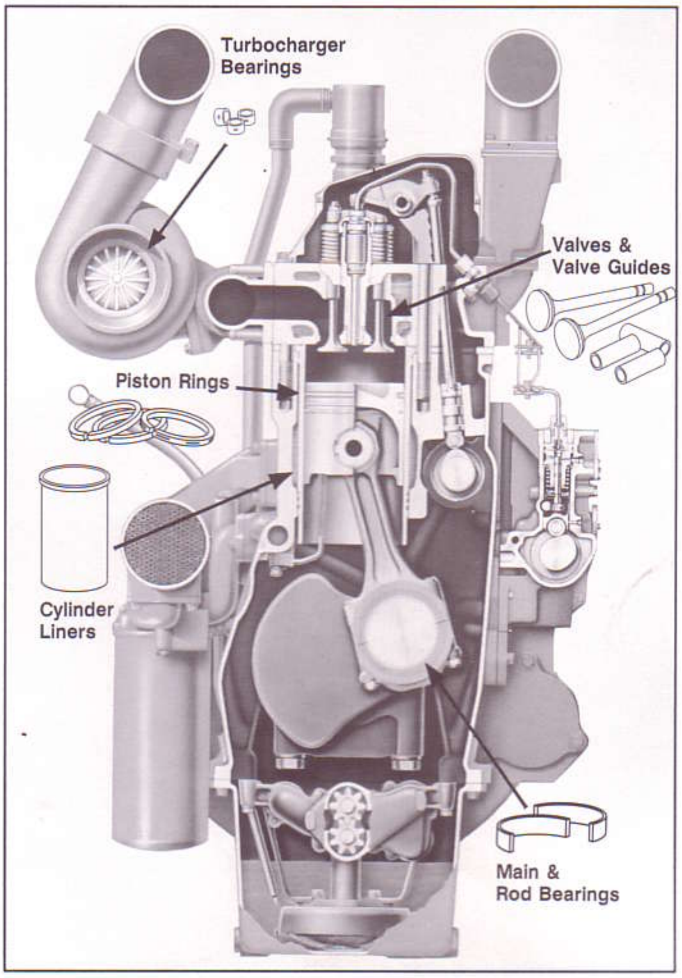


Bearing showing abnormal wear.

Abnormal wear is any wear other than that from normal engine operation. Generally, abnormal wear results from incorrect maintenance or operating technique. Using the wrong oil, extending oil changes intervals, not maintaining the coolant conditioner concentration, and inadequate machine warm-up are typical practices that cause abnormal wear and premature engine failure.

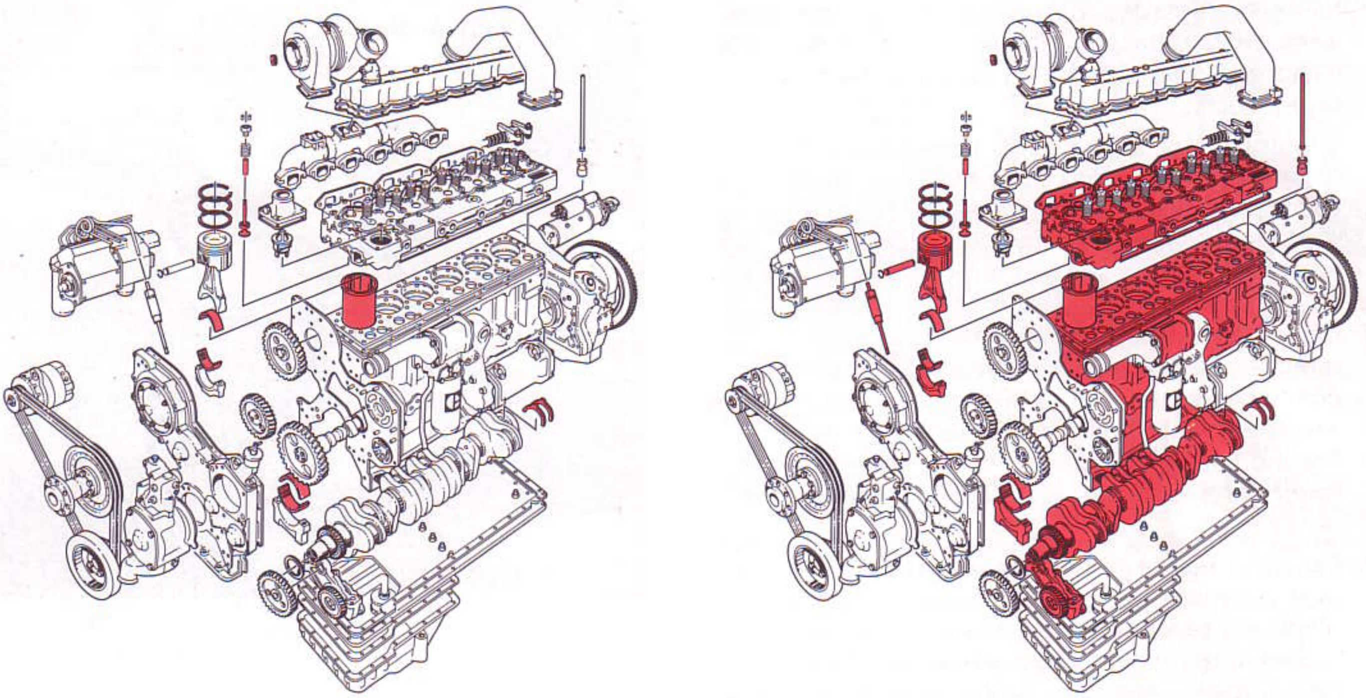
It is important to understand that there are only five major wear items in a diesel engine, and they're worth repeating:

- cylinder liners
- piston rings
- valves, guides, and seats
- main and rod bearings
- turbocharger bearings and seals



If these wear parts are replaced before they wear out approximately 80% of major engine failures can be eliminated.

These parts are relatively inexpensive, and if replaced on a timely basis, expensive components like cylinder heads, blocks, crankshafts and connecting rods should never need replacement.



Wear items replaced when repairing before failure (on the left). Parts replaced after failure (on the right). Think of the unnecessary costs associated with after failure repairs.

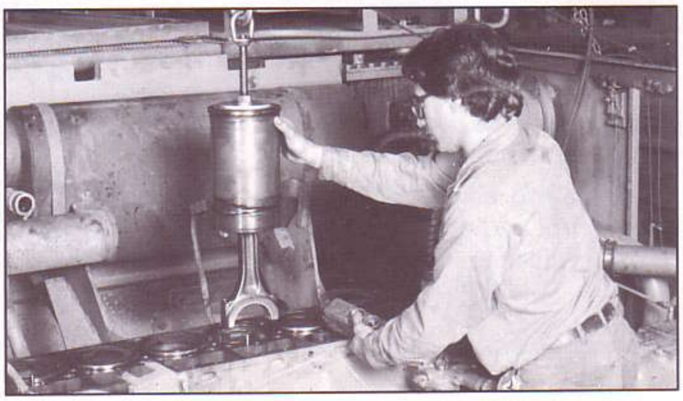
Repair Before Failure

This concept is the basis for the management strategy of repairing before failure. Let's look at a quick comparison between before and after failure repairs so we clearly understand how repairing before failure benefits the customer.

In our after failure example the customer ignores the repair indicators and continues operating the engine until a main bearing fails causing major damage to the crankshaft. In fact the damage is to the point that the crankshaft cannot be used as a core for a remanufactured crankshaft - adding substantially to the repair costs.

In our before failure example the engine is maintained correctly and the repair indicators are monitored. When an S•O•S report warns of bearing wear the engine is promptly scheduled for repair - before major failure can occur. The inexpensive bearings are replaced and there is no damage to the crankshaft or other components.

Using this example, let's summarize the customer benefits of repairing before failure.



Nobody knows Cat equipment design and wear trends as well as Caterpillar and Cat Dealers. They regularly pool information to develop wear trends for accurately interpreting S•O•S test results. Other oil analysis programs simply don't have this critical information. The bottom line is, S•O•S is the only program that can determine when wear trends go from acceptable to unacceptable - indicating a problem.

Used regularly, S•O•S can catch problems early so they can be fixed in minimal time and with minimal costs to the customer.

Engine Repair Indicator Kit

One of the easiest ways to determine the overall condition of an engine is to perform some simple checks or tests. That is the purpose for the Engine Repair Indicator Kit (ERIK). The kit includes the basic tools needed to evaluate the engine condition and determine if a before failure overhaul is needed, or if further diagnosis is required.

The kit is convenient and easy to use. In the kit are such tools as:

- Temperature Recorder Labels
- Coolant Conditioner Test Kit
- Filter Cutter
- Crankcase Pressure Gauge

Also included is helpful literature such as an Overhaul Estimator Form, Engine Evaluation Worksheet and Special Instructions that give you the basic information needed to complete a thorough engine evaluation. Dealer salesmen are finding the kit useful in building credibility and professionalism with their customers.

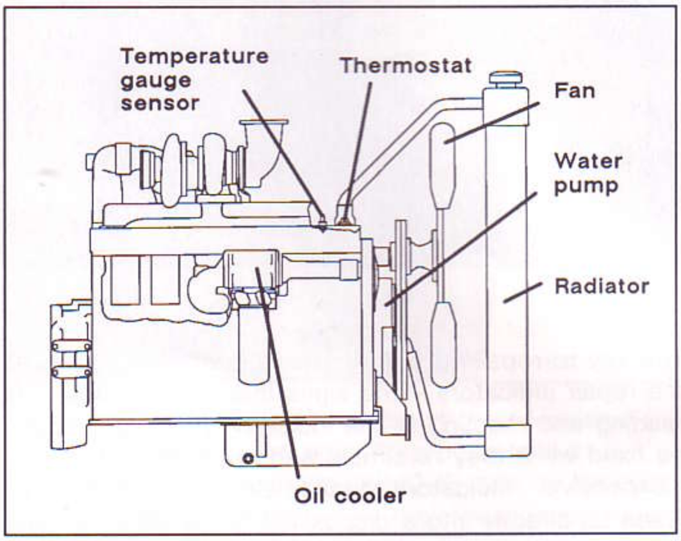
Now let's look at each of the diesel engine systems individually.

I. Cooling System

Over 40% of engine failures result from cooling system problems. Of the five systems, the cooling system is the most critical to engine life.

Over 40% of engine failures are due to cooling system problems.

The components that make up the cooling system include the following.

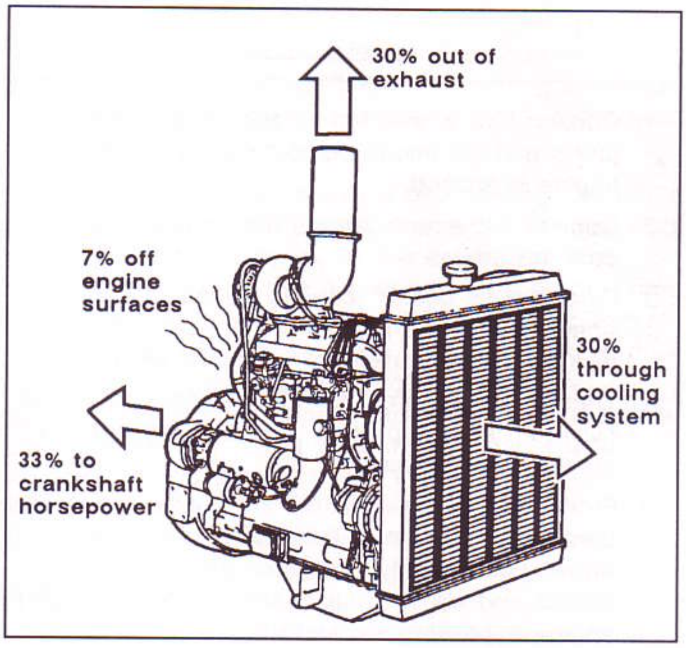


- **Water Pump** - The water pump provides continuous circulation of coolant whenever the engine is turning. Water pumps on Cat engines are generally gear driven, except on the 3208, 3114, and 3116 Engines which have belt driven water pumps.
- **Radiator** - The radiator transfers heat away from the coolant, lowering coolant temperature. Coolant flows through the radiator tubes while air circulates around the tubes providing a transfer of heat to the atmosphere. We have three styles of radiators, conventional-style, folded core, and the modular core radiator.
- **Coolant** - Coolant is a mixture of water, antifreeze (glycol), and coolant conditioner (inhibitor). For proper cooling, each must be maintained in the correct proportion.
- **Thermostat** - Technically the thermostat is called a temperature regulator. The thermostat assists in engine warm-up and helps maintain coolant and engine temperature during operation. When the engine is cold the thermostat allows coolant circulation just through the engine, bypassing the radiator (to help the engine warm-up). When the engine is at proper operating temperature the thermostat opens to allow coolant flow through the radiator (so cooling takes place). The thermostat continually opens and closes as the coolant temperature changes.
- **Water Temperature Gauge** - The temperature gauge indicates the temperature of the coolant. The recommended operating range is generally between 190°-210°F (88°-99°C).
- **Fan** - The fan forces air around the radiator tubes to transfer heat out of the coolant and decrease coolant temperature. Fans are belt driven off a crankshaft pulley.
- **Oil Coolers** - Oil coolers function to maintain the correct temperature of engine, transmission and hydraulic oil. There are two basic types: oil to coolant and oil to air.

  Oil to coolant coolers are used most often for cooling engine and transmission oil. Oil flows through tubes while coolant flows around the tubes picking up heat and lowering the oil temperature.

  Oil to air coolers are used most often for hydraulic systems, where a much greater temperature drop is required, such as on many excavators. Air to oil coolers are similar in design and principle to radiators. Air blows across the surface of oil cooler tubes dissipating heat away from the oil to the atmosphere.

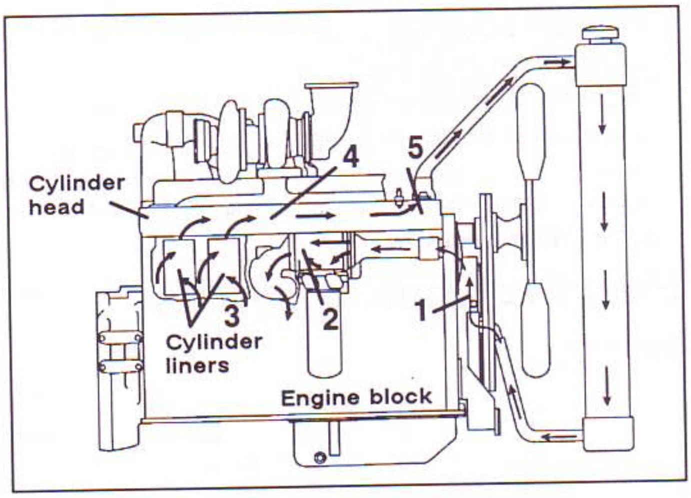
How the Cooling System Works



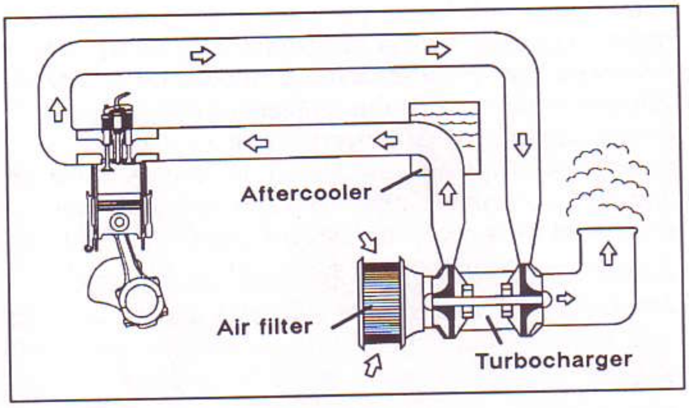
The primary function of the cooling system is to maintain correct engine temperature by taking away unwanted heat generated by combustion and friction. Approximately 33% of the heat energy developed during combustion is converted into usable horsepower, 7% radiates directly off engine surfaces and 30% out the exhaust. The remaining 30% is dissipated by the cooling system.

Coolant circulates through passages in the engine called water or coolant jackets. The coolant absorbs heat from the hot engine surfaces and carries it to the radiator where it transfers to the atmosphere.

The cooling system also helps maintain the correct temperature of engine, transmission and hydraulic oil through the use of oil coolers. Now let's look in more detail at how coolant flows through the engine.



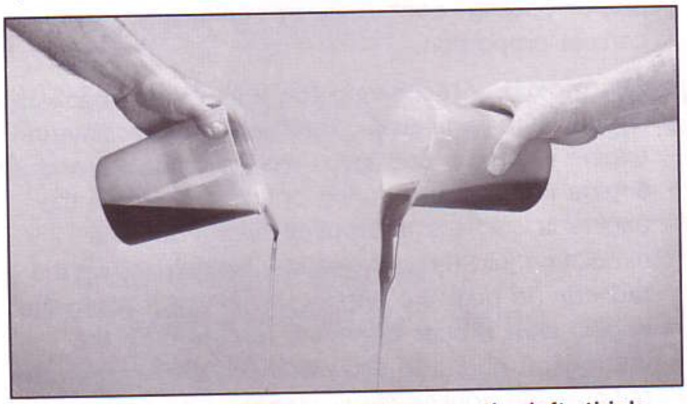
1. Coolant flow is initiated by the water pump that starts and continues pumping as soon as the engine is started.
2. Coolant circulates through the engine oil cooler to cool the engine oil.
3. From the oil cooler, coolant travels into the engine block and around the hot cylinder liners picking up heat and cooling engine parts.
4. Then it travels through intricate passages in the cylinder head(s) picking up more heat around the critical valve areas.
5. From the cylinder head(s) the coolant goes to the thermostat and on to the radiator for cooling. If the engine is cold, the thermostat will remain closed and will recirculate the coolant through the engine bypassing the radiator.



Engines with turbochargers and aftercoolers circulate partial flow of coolant from the water pump directly to the aftercooler. Here the coolant is used to lower the air temperature so that more air can be packed in the cylinder. This allows more fuel to be burned and creates higher engine horsepower output. In addition, some machines have torque converter and transmission oil coolers which are also cooled by engine coolant.

Diagnosing Cooling System Problems

Which causes the most engine failures...problems with the cooling system or the lubrication system? Initially most people say the lubrication system, however the correct answer is the cooling system. A cooling system that runs too cold causes marginal lubrication because the low temperature prevents the oil from warming up so that it can flow and coat parts adequately. A cooling system that runs too hot also causes marginal lubrication because the high temperatures break down the oil properties so that parts are not protected correctly. Both cases of marginal lubrication can be traced back to cooling system problems



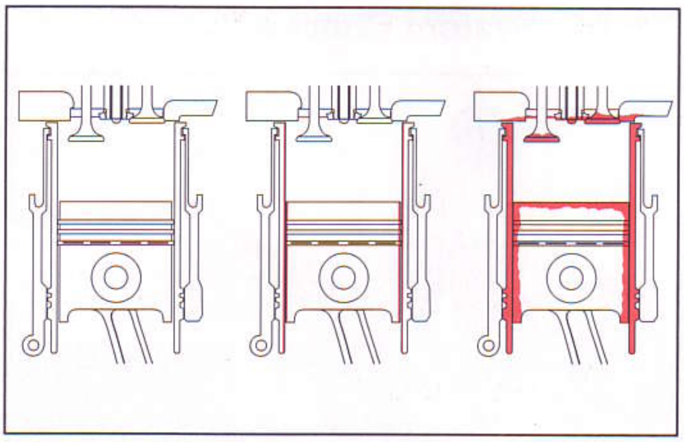
Oil at normal operating temperature on the left, thick viscous oil at low temperature on the right.

Cooling and lubrication are closely related because temperature greatly affects the oil's ability to lubricate and protect parts properly.

Generally, engines are designed to operate between 190°-210°F (88°-99°C) - and they will not operate well, or live up to their expected life, if continually run either colder or hotter than this. If the engine runs hotter (overheating), or if it continually operates below this temperature (overcooling), the result is the same - excessive engine wear and damage. Let's examine overheating and overcooling and the indicators or warning signs of these problems.

Overheating

Overheating is by far the most well-known cooling system problem. If left unresolved it will almost always cause quick, catastrophic engine failure, sometimes in a matter of minutes.



This illustrates the heat build-up leading to a seizure condition. Note how heat affects all parts forming the combustion chamber, including the valves, fuel nozzle and cylinder head.

Without proper cooling, temperatures inside an engine will soar, - especially around the combustion chamber where extreme hot spots can develop. Overheating causes parts to expand causing more friction, and thus more heat. Temperatures continue to increase until the parts cannot move and will ultimately seize. For example, a piston will expand causing the clearance between it and the cylinder liner to decrease to the point that the piston seizes in the liner. Often in this case, the piston is pulled apart from the connecting rod and piston pin allowing the rod to break through the liner and go through the side of the engine block. Catastrophic failure - and without proper cooling it takes only a short time for such a failure to occur.

Overheating also causes a breakdown of the oil which is the main safeguard against wear. As temperatures increase, the oil thins out, destroying its lubricating qualities. In this thinned out state the oil doesn't have the strength to support the parts adequately. It doesn't provide a barrier between moving surfaces. The result is metal-to-metal contact and excessive wear.

Indicators of Overheating

- **S•O•S - high wear metals & oxidation**
- **High reading on temperature gauge**
- **Cracked cylinder head**
- **Turbocharger failures**
- **High temperature label readings**

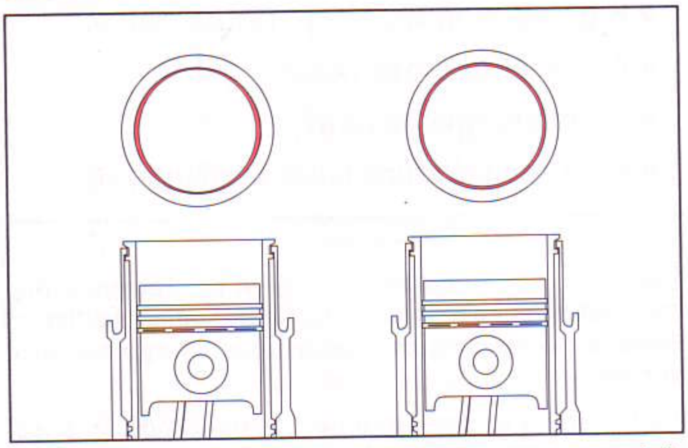
Overheating often causes excessive or premature ring and liner wear, piston scuffing, and bearing scuffing. Extreme overheating can also cause the cylinder head to crack.

It's important to note here how overheating can affect the entire engine. Take for example a customer who had a cracked cylinder head due to overheating, replaced it and then had a piston seizure a short time later. The known problem was the cracked cylinder head. It was easy to diagnose. But unknown to the customer was the additional problem of scuffed pistons. When the engine temperature increased the pistons expanded, and the oil thinned out, causing scuffing. The scuffing caused increased friction which eventually caused one of the pistons to seize. Both problems, the cracked head and scuffed pistons, occurred at the same time, but only one, the cracked cylinder head, was diagnosed. The point is to think of all the consequences of an overheating problem, beyond the most obvious.

S•O•S reports on engines with overheating typically show elevated concentrations of wear metals, with no substantial increase in dirt (silicon). Iron (cylinder liners), chrome (piston rings) and lead (bearing overlay) readings may increase due to the effects of marginal lubrication from overheating. In addition, since heat acts as a catalyst to the oxidation process, infrared test results may show elevated oxidation readings.

Overcooling

Overcooling is less understood than overheating, but the results can be just as damaging. Both cause excessive wear.



Elliptically shaped piston at ambient temperature on left. The same piston at normal operating temperature on right.

Overcooling prevents the oil and parts from getting to the correct temperature. This is especially prevalent during engine start-up and in low ambient temperature applications. In these situations the oil is cold and thick and doesn't flow correctly or quickly enough, resulting in marginal lubrication. Also, when parts don't reach the correct operating temperature they don't seat together properly - causing wear. Pistons are a good example. If overcooling occurs, pistons don't expand to fit correctly in the cylinder. In effect you have an "out-of-round" (elliptically-shaped) piston moving up and down in a round cylinder liner. The result is excessive wear around the piston skirt.

Indicators of Overcooling

- **Not enough heat in the cab**
- **S•O•S - high wear metals, no oxidation**
- **Low reading on temperature gauge**
- **Scuffed bearings or pistons**

Instead of immediate engine failure, which is common with overheating, overcooling causes wear that progresses over a longer time. If an engine will normally run 8000 hours to overhaul in an application, with overcooling it will typically run only 6000 hours.

Overcooling is harder to detect, but S•O•S is still the best indicator. The S•O•S results will be similar to overheating. However, since there is no excessive heat, there will be no increased oxidation as occurs during overheating conditions. In addition to encouraging enrollment in S•O•S, check the following points to help insure the cooling system is operating correctly.

Cooling System Checks

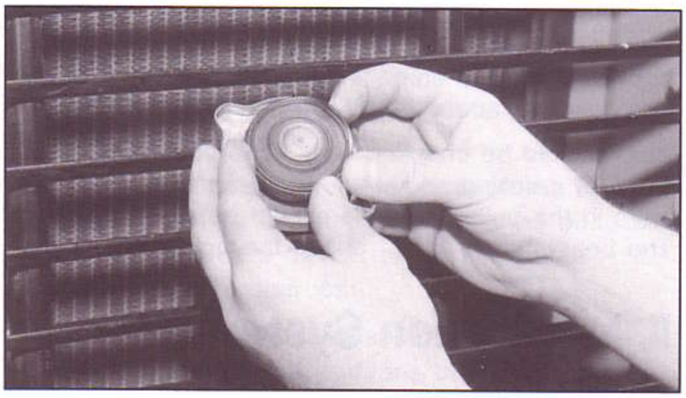
Thermostats - When the engine is cold the thermostat assists the engine in warming-up and reaching correct operating temperature quickly. You can't tell by looking at the thermostat if it's working correctly, however there are some indicators that will tell you if it isn't working correctly. In cold climates, if a thermostat is stuck open it will take an excessively long time for the engine to warm-up and little or no heat will be available to heat the cab. If the thermostat is stuck closed the engine will overheat. In this case the engine will be very hot while the radiator, hoses and tubes are cool, indicating the coolant is not going through the radiator. It is important to remind owners and operators to never operate a Cat engine or machine without a thermostat - overheating can result.

Coolant Temperature Gauge - If you suspect a faulty gauge, you can place a few temperature labels on the engine and radiator to get an approximate temperature reading. If you still suspect a problem, the service department can use a Thermistor Thermometer for a more accurate reading and for further investigation.

Emphasize with customers the importance of using correct start-up procedures. Remind them to not start operating until the engine has reached the correct temperature, indicated by the coolant temperature gauge pointing in the green area. Also, warn them if the gauge points in the red area, indicating overheating, the machine should be shut down or the loads reduced immediately so the problem can be investigated.

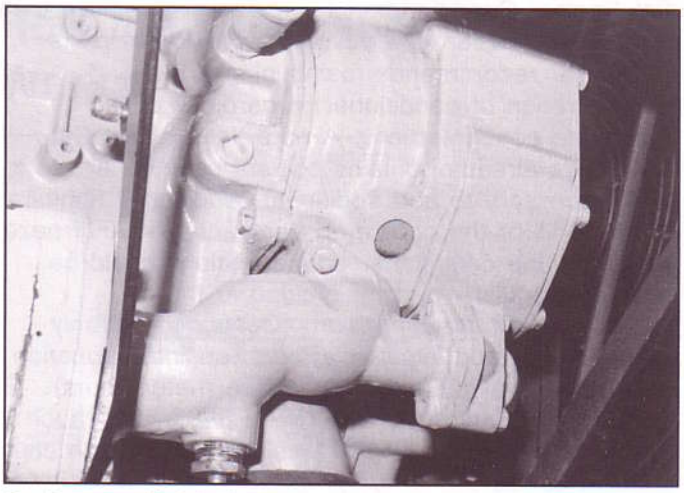
Radiator & Fan – The radiator, fan and the surrounding area must be free of debris for adequate cooling. Cleaning must be performed as often as needed. This might be monthly, weekly, nightly or even every few hours, such as in some landfill or forestry applications. Also remember that loose or broken fan blades and belts will reduce cooling system efficiency.

Reversible fans are frequently used on machines working in landfill and other applications where debris can hinder cooling efficiency. Reversible fan blades can be turned 180° to either blow air from the engine or to suck it through the radiator. It is important that machines with reversible fans follow the Cat recommendations outlined in the machine literature, otherwise overheating can result.



Radiator Cap Seal – The rubber seal in the radiator cap must be in good condition for correct sealing and pressurizing of the cooling system. If there are cracks in the seal or signs around the radiator fill area indicating the coolant has boiled over, the seal probably needs replacement.

Cat cooling systems generally operate under 8–16 psi (55–110 kPa) pressure. This raises the boiling point of the coolant. If there is inadequate system pressure, the coolant will boil over and the engine will overheat.



Coolant or oil dripping from the weep hole on the side of the water pump indicates wear.

Water Pump – The major indicator of water pump (coolant pump) wear is coolant or oil dripping from the weep hole on the side of the pump. This indicates the pump seal is wearing and means the pump will need replacement soon.

Note, slight draining of coolant or oil from the weep hole is normal. A leaky or worn pump seal can be identified if there is continuous flow or measurable coolant loss every day.

Coolant – Coolant is the mixture of water, antifreeze (glycol) and coolant conditioner (inhibitor). Cat Antifreeze protects against boil-overs, freezing and corrosion. It's significant to note that antifreeze is needed not only in cold weather, but warm climates as well. In warm weather, glycol (antifreeze) is needed to: raise the boiling point, prevent boil-overs and overheating, to keep scale deposits to a minimum.

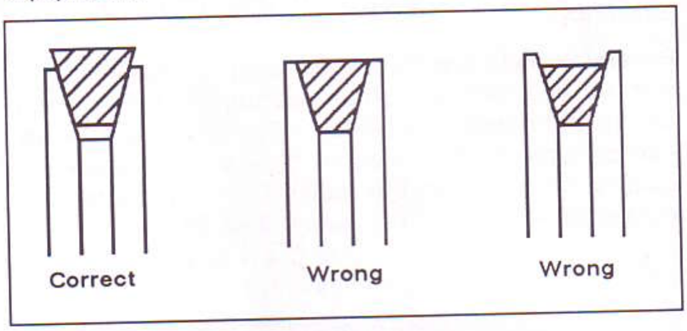
Caterpillar recommends maintaining the glycol concentration in coolant between 30-60%, depending on the application.

Cat Coolant Conditioner (inhibitor) is the additive that prevents corrosion and cavitation erosion of parts. Caterpillar recommends maintaining a 3-6% concentration of conditioner, regardless of the antifreeze concentration. A note here is that Cat Antifreeze already contains coolant conditioner, so it is NOT necessary to add additional conditioner (inhibitor) on initial fill of the cooling system with Cat Antifreeze. However, the conditioner concentration should be checked regularly and maintained at the recommended concentration. Generally it is only necessary to add inhibitor at each engine lubrication service interval (250 or 500 service meter hours). Be sure the concentration is between 3-6%, too much corrosion inhibitor will form insoluble salts which cause excessive wear.

Caviation erosion will pit and corrode parts such as this precombustion chamber (top) and cylinder liner (bottom).

Without the needed conditioner, severe cavitation erosion will pit and corrode the outer cylinder liner surfaces and surfaces of the block next to the liners. Erosion can be very damaging. If not stopped it can progress completely through the liner or cylinder block walls.

Encourage customers to maintain their coolant according to the recommended procedures in the Lubrication and Maintenance Guide. Also, encourage the use of Cat Antifreeze and Cat Coolant Conditioner. Both products are formulated to Caterpillar specifications to provide the best protection for Cat equipment.



Belts and Pulleys – The fan is belt driven off the crankshaft as are some water pumps. Cat recommends about 1" (25 mm) play in the belts.

Belts should be checked daily for proper tension, and signs of cracking and wear. The correct position of belts in the pulley grooves should be as illustrated. The belts should "ride" above the pulley grooves.

II. Lubrication System

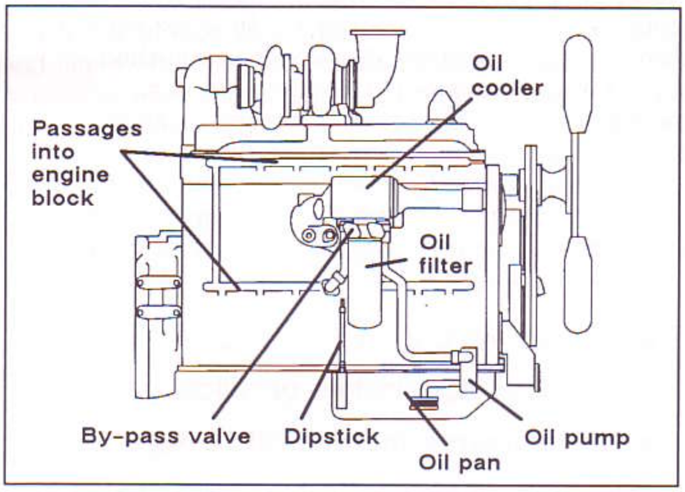
The engine lubricating system has three main functions: to clean, cool, and lubricate parts.

Engine Oil

1. Cleans
2. Cools
3. Lubricates

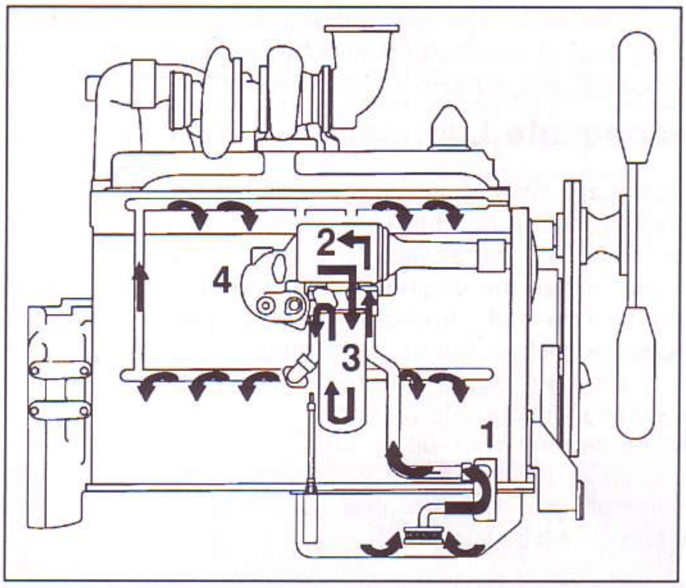
- **Cleaning:** Oil cleans parts by carrying away damaging metal particles that materialize during normal engine operation. Oil also cleans the cylinder walls and carries away carbon and lacquer deposits produced during combustion.
- **Cooling:** The second function of oil is to cool part by absorbing and carrying heat away.
- **Lubricating:** Thirdly, oil forms a thin film or layer between the surfaces of moving parts to support and separate them. This prevents metal-to-metal contact that causes excessive wear.

The components of the lubrication system include the following.



- **Oil Pump** – The oil pump operates whenever the engine is turning to provide continuous circulation of oil through the engine.
- **Oil Cooler** – Coolant circulates through the oil cooler providing a heat transfer, from the oil to the coolant. This lowers the oil temperature and protects the oil properties.
- **Oil Filter** – The oil filter cleans the oil by collecting metal particles and other debris that can damage engine parts.
- **Oil Level Gauge (dipstick)** – The dipstick provides a method to check the amount of oil in the engine.
- **Oil Pressure Gauge** – The oil pressure gauge indicates the pressure in the engine lubrication system during engine operation.
- **Oil Pan** – The oil pan (sump) bolts to the bottom of the engine and is the reservoir for the engine oil.
- **Oil Fill Pipe** – This is where oil is poured into the engine.

How the Lubrication System Works



1. Oil travels from the oil pan (sump), at the bottom of the engine, up through the oil pump and
2. then to the oil cooler. Here the oil is cooled by engine coolant.
3. Then the oil goes through the oil filter(s) where debris and contaminants are removed.
4. Clean oil then moves into the oil manifold where it goes in two directions:
   A. into the engine to lubricate components, such as the bearings, gears, pistons, liners, valves, etc.

   B. and a smaller flow directly to the turbocharger.

The oil then returns to the engine oil sump (pan) to start the cycle again. A bypass valve in the filter base allows unfiltered oil to by-pass a plugged filter so the engine will always have some oil. When the oil is cold an oil cooler bypass valve bypasses oil around the oil cooler during start-up.

Diagnosing Lubrication System Problems

There are two major lubrication system problems that can cause excessive engine wear: inadequate lubrication and contaminants in the oil.

Inadequate Lubrication

Inadequate lubrication, or marginal lubrication, can develop from a number of causes. The most common, and the easiest to correct, is cold engine starts. When the engine is cold, the oil is thick and doesn't flow well. If engine speed or load is increased before the oil is warmed-up marginal lubrication will occur. In effect, the parts will be operating without adequate oil. Following the recommended start-up procedures will eliminate this problem and help assure long engine life. Note that in extremely low ambient temperatures auxiliary oil heaters may be required.

Lack of Lube Indicators

- **Low oil pressure**
- **Scuffed bearings**

Other causes of inadequate lubrication include:

Wrong Viscosity of Oil

If the oil is too thin, it will not coat the parts adequately; and if it's too viscous, or thick, it will not flow correctly. In either case, the oil is not providing adequate protection.

Not Enough Oil

If there isn't enough oil in the engine, there of course, will be inadequate protection between moving parts. The result will be almost immediate engine damage. Note also that even operating with a low oil level causes problems. It allows air into the system, lowering the lubrication system pressure, which in turn prevents sufficient lubrication to some parts.

Overcooling

When an engine runs too cold it doesn't get hot enough to boil off water produced during combustion. The water then mixes with other combustion by-products forming acids. The acids damage oil properties causing inadequate lubrication and excessive wear.

Contaminants In The Oil

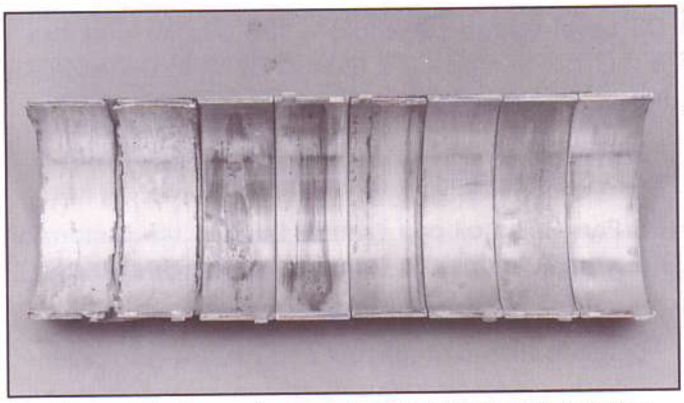
The second type of lubrication system problem is contaminated oil. The leading cause is extended oil change periods. When oil changes are pushed beyond the recommended period there is a breakdown of the oil itself and it loses its ability to suspend contaminants, something similar to a contaminant overload. When this happens, contaminants embed themselves in bearing surfaces and other moving parts causing damage and wear.

Indicators of Contaminated Oil

- **S•O•S - high metals or silicon**
- **Contaminants in used oil filters**
- **Scratched bearings, pistons or rings**
- **Milky colored oil (water or antifreeze)**

Dirt and metal particles are the most common contaminants, but soot, water, and antifreeze also contaminate the oil causing excessive engine wear.

Note: Contaminated oil is the single largest cause of engine crankshaft bearing failure. Between 70% and 80% of all crankshaft bearing failures are caused by contaminated oil.



Bearings on left are damaged from debris and fatigue; ones on right show normal wear.

By far, bearings are the most sensitive engine parts to oil related problems, especially turbocharger bearings. If a lubrication problem exists, the first sign will be worn turbocharger bearings. Main and rod bearings are the next most susceptible parts. But because they are thicker, they can often survive marginal lubrication longer than the thinner, faster moving turbocharger bearings. The point to remember is; if bearing wear is a problem, the cause will normally be found in the lubrication system.

Before leaving the discussion on contaminated oil here's one important message that needs to be discussed with every equipment owner. One of the best ways to extend engine life is to simply change oil and filters according to recommended schedules. Also to inspect filters regularly. These simple procedures cannot be overstressed.

Oil Filters

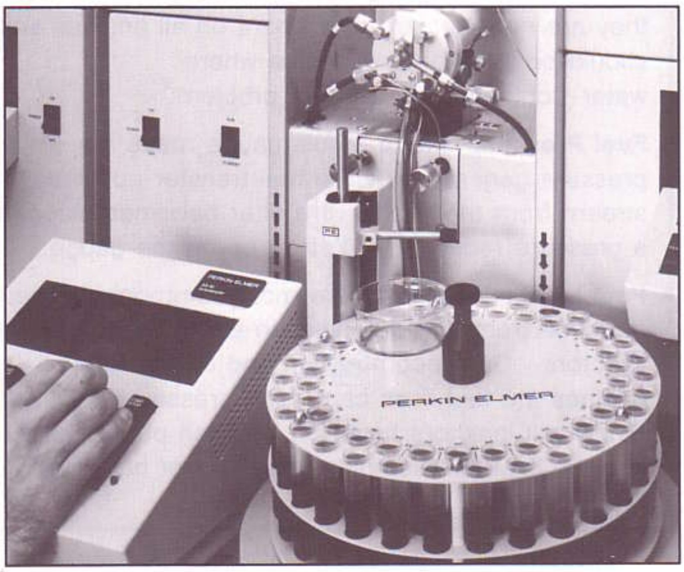
It's a good practice for owners and operators to cut open used oil filters and examine the filter paper and oil for metal particles.

Cutting open oil filters is the best visual check for detecting internal engine wear.

Other than S•O•S, this is the best method for detecting internal engine wear. It's a practice that should be a regular part of the oil and filter change procedure.

S•O•S

We've already discussed S•O•S as a indicator for signaling accelerated engine wear. It should also be noted that it monitors the condition of the oil. S•O•S indicates if the oil is contaminated or if the properties of the oil are breaking down.



Here are some other areas that can warn of lubrication system problems.

Low Oil Pressure

If an oil filter plugs, a bypass valve will open and allow unfiltered oil to the engine. The operator may notice a slight reduction of pressure on the gauge, for example, from 50 to 45 psi (345 to 310 kPa). When the filter is replaced, the pressure will go back up to the previous level. Extreme low oil pressure may indicate a dangerous problem possibly caused by an insufficient amount of oil, a malfunctioning oil pressure relief valve, or worn oil pump gears.

Cat Filters and Fluids

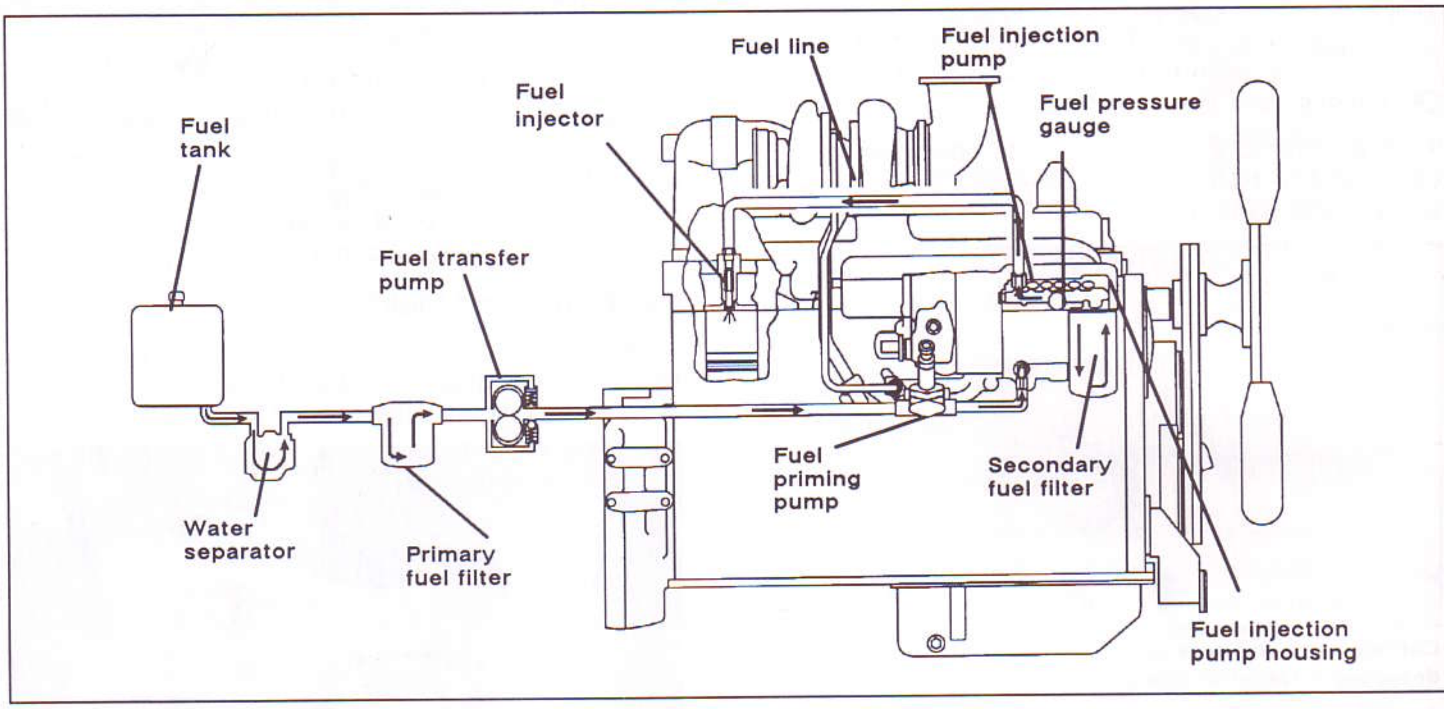
Caterpillar Filters and Fluids are specifically designed to provide Cat engines and equipment the best protection against excessive and costly wear.

Cat Filters are manufactured to meet exacting requirements of each engine model. These specifications help prevent the filter from plugging prematurely, rupturing or passing damaging debris.

Cat Diesel Engine Oil is specifically formulated to reduce deposits and provide the best wear protection for Cat diesel engines. Cat Engine Oil also provides excellent protection and is recommended for mixed fleets or other brands of engines.

III. Fuel System

It is the function of the fuel injection pumps and injectors to supply fuel into each cylinder in the correct amount and at the right time for efficient combustion. The components of the fuel system include the following.



Direct Injection Engine

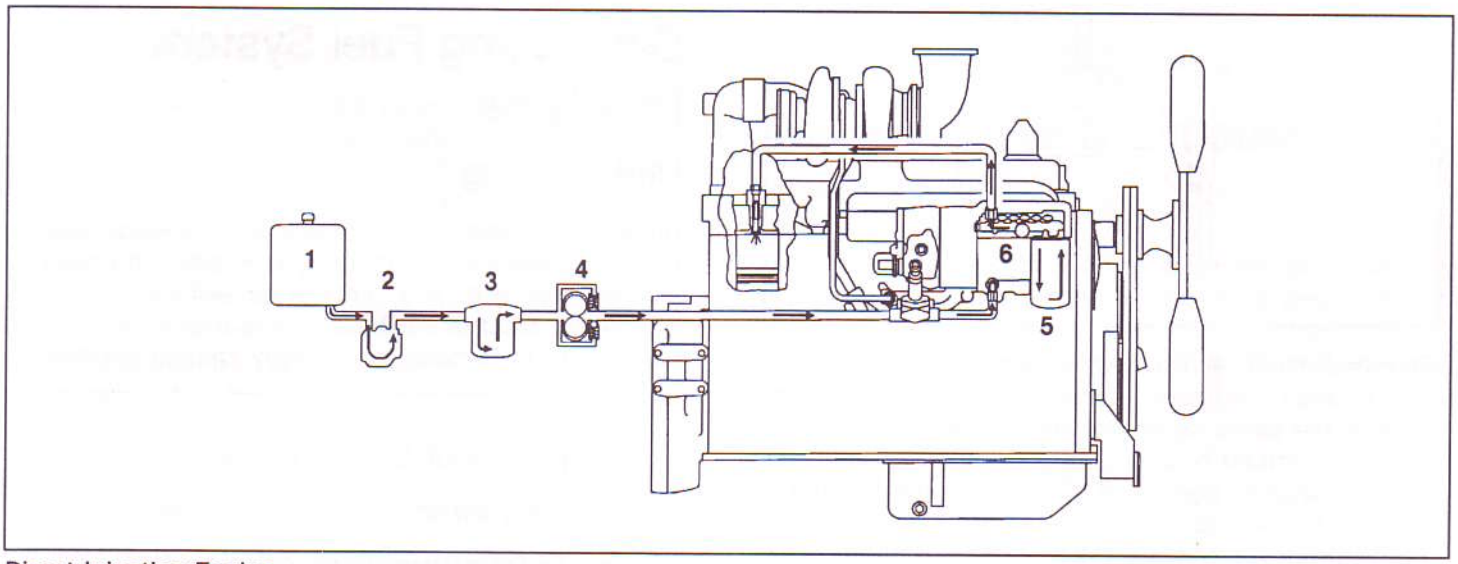
- **Fuel Tank** – The tank is the reservoir for holding fuel.
- **Fuel Transfer Pump** – The transfer pump maintains a constant flow of low-pressure fuel from the fuel tank to the engine fuel system. Note, the transfer pump is different from the fuel injection pumps.
- **Fuel Injection Housing** – All engines, except those with unit injectors, have a fuel injection housing that holds the individual fuel injection pumps (one per cylinder).
- **Fuel Injection Pumps** – There is one fuel injection pump for each cylinder. Unlike the fuel transfer pump which is low pressure, the fuel injection pumps operate at high pressure. Injection pressures can run from 2,800 to 20,000 psi (19,290 to 137,800 kPa). Each pump meters the correct amount of fuel and pumps it, at a high pressure, through metal lines to each fuel injector.
- **Unit Injectors** – The unit injector combines a fuel injection pump and a fuel injector into one assembly. Unit injectors eliminate high pressure fuel lines between the pump and injector allowing for higher fuel injection pressures.
- **Fuel Filters** – Fuel passes first through a primary, then a secondary fuel filter. It's critical to have clean fuel for these high pressure pumps. Some of the clearances between parts are as small as a few millionths of an inch and even the smallest debris can cause damage.
- **Water Separator** – Water separators are used to protect against rust caused by water-contaminated fuel. All 3208 engines have water separators. Note they are not standard equipment on all engines and should be used on any engine where water-contaminated fuel is a problem.
- **Fuel Pressure Gauge** – This gauge reads the pressure generated by the fuel transfer pump down stream from the filters. If a filter becomes plugged a pressure reduction will show up on the gauge.
- **Fuel Lines** – Fuel lines are most commonly defined as those from the fuel injection pump housing to the injectors. On precombustion and direct injection engines the fuel lines carry high pressure fuel. Since unit injectors have the injection pumps built into the injector assembly, they do not have high pressure lines.

How the Fuel System Works

There are two methods of delivering fuel into the combustion chamber; the first is precombustion, where fuel begins ignition in a precombustion chamber before going into the cylinder; and the second is direct injection, in which the fuel is injected directly into the cylinder for combustion.

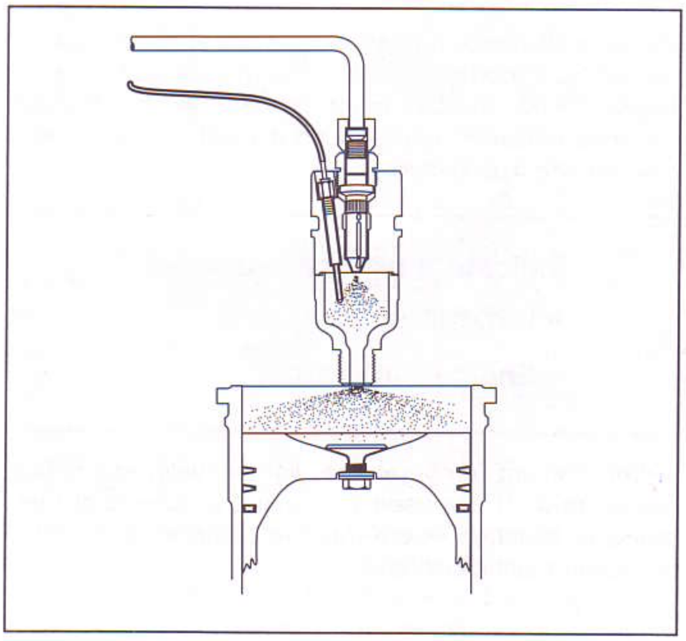
It is also important to understand unit fuel injectors which are used on many of the latest model Cat engines. Unit injectors use a direct injection method of fuel delivery but they are different from engines with traditional precombustion and direct injection systems.

The fuel travels through all Cat Engines in basically the same way, up until the point of fuel injection. (1) Fuel goes from the tank, (2) through a water separator, (3) through a primary fuel filter, and (4) into the fuel transfer pump. (The primary filter can be before or after the transfer pump). From the transfer pump fuel (5) goes to a secondary filter, and then either (6) to a fuel injection pump (precombustion and direct injection) or to a unit fuel injector.



Direct Injection Engine

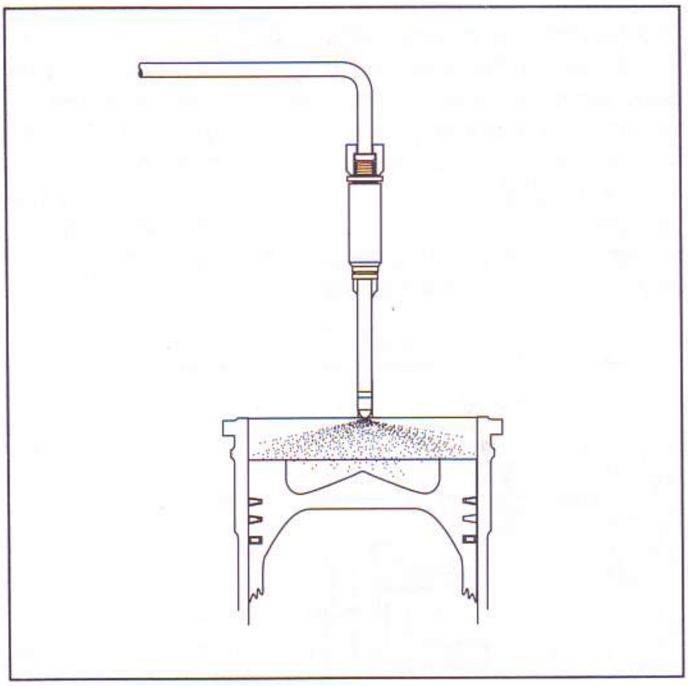
Precombustion



The precombustion chamber (PC) system is found primarily on older model engines. Fuel is pulled from the tank by the fuel transfer pump and pumped through the primary and secondary fuel filters to the fuel injection pump housing where the individual fuel pumps are located (one per cylinder). The fuel injection pumps force fuel through high pressure fuel lines to the fuel nozzles mounted in the cylinder head. A precision drilled hole in the end of each nozzle atomizes fuel as it enters the precombustion chamber. As the fuel begins to ignite, the heat of combustion forces the remaining fuel and air mixture through an orifice in the precombustion chamber into the cylinder.

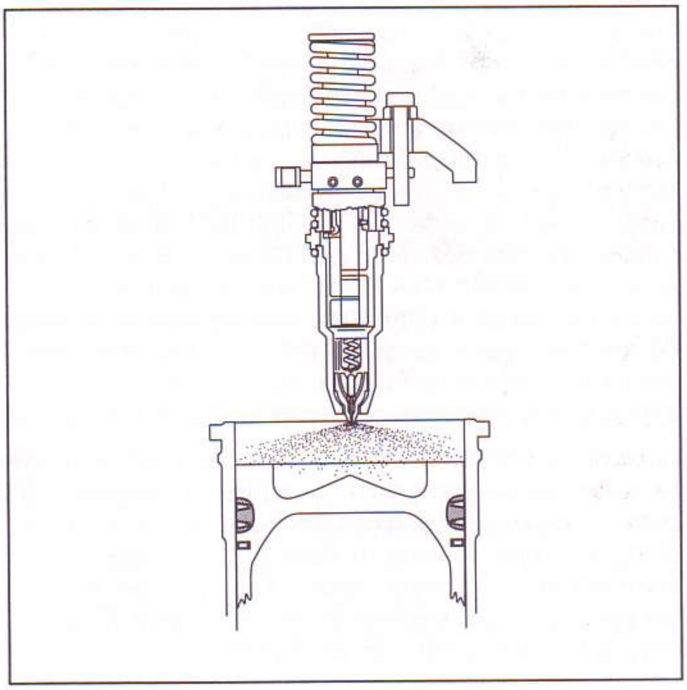
Glow plugs are mounted in the PC chamber housings to warm the air and assist in starting PC engines. It's easy to identify PC engines because of the electrical glow plug wires running to each precombustion chamber in the cylinder head. And, you can easily tell pistons on PC engines by the steel heat plug mounted in the center on each piston.

Direct Injection



On direct injection (DI) engines fuel travels from the tank through the filters, pump, and lines to the injector housing the same as on precombustion engines. However, instead of pre-igniting the fuel, direct injection engines inject fuel directly into the cylinder. You can tell pistons on DI engines because the top of the piston crown has a conical crater design and no steel heat plug.

Unit Injectors



Many of the latest model Cat engines, including the 3500 and 1.1 Liter Engines use unit fuel injectors. Each unit injector has a high pressure injection pump and injector nozzle built-in each unit assembly. There is one unit injector for each cylinder. They are mounted in the cylinder head. Low pressure fuel is delivered from the fuel transfer pump to each unit injector, then through the injector assembly directly into the cylinder. A rocker arm assembly, similar to that used to operate the engine valves, operates the fuel injection pumps. By eliminating the fuel lines, the injector pressures can be increased resulting in more efficient atomization and combustion.

Diagnosing Fuel System Problems

Underfueling

Underfueling occurs when there is not enough fuel to meet the power demands on the engine. It doesn't normally cause engine damage but will cause a lack of power. Most often the cause is a plugged fuel filter, and the remedy is to simply change the filter.

Indicators of Underfueling

- **Low power**
- **Low fuel pressure (plugged filter)**

Correct Fuel

The type of diesel fuel as well as the maintenance of the fuel is important to the performance and life of an engine. First, the fuel must be clean - free of water and contaminants, and second it must be the correct type for the application.

Indicators of Incorrect Fuel

- **Difficult starting**
- **Engine cutting out**

In low ambient temperatures, lighter fuels, like diesel fuel number 1, are used to prevent problems of fuel jelling (a situation where the fuel coagulates preventing sufficient flow).

In areas outside North America, it's important that owners match the TBN number (Total Base Number) of the engine oil to the sulfur content of the fuel. Normally TBN additives in the engine oil neutralize fuel sulfur by-products which result from combustion. However, if the concentration of sulfur in the fuel is too high, or the oil TBN too low, sulfuric acid will develop. This can cause corrosion and excessive wear of piston rings, bearings, and liners. To counter such problems customers can change to a higher TBN oil or shorten the oil change intervals. Note: recommend shortening the oil change intervals only after thorough discussion with the appropriate Caterpillar personnel.

Overfueling

Overfueling occurs when too much fuel is injected into the cylinder. Excessive black exhaust smoke is the leading warning sign. There are many causes, such as a high fuel rack setting, misadjusted air/fuel ratio control or faulty fuel injector. All involve the fuel system and must be handled by appropriate dealership service personnel.

Indicators of Overfueling or Incorrect Atomization

- **Black smoke**
- **Increased fuel consumption**
- **S•O•S showing fuel in the oil**

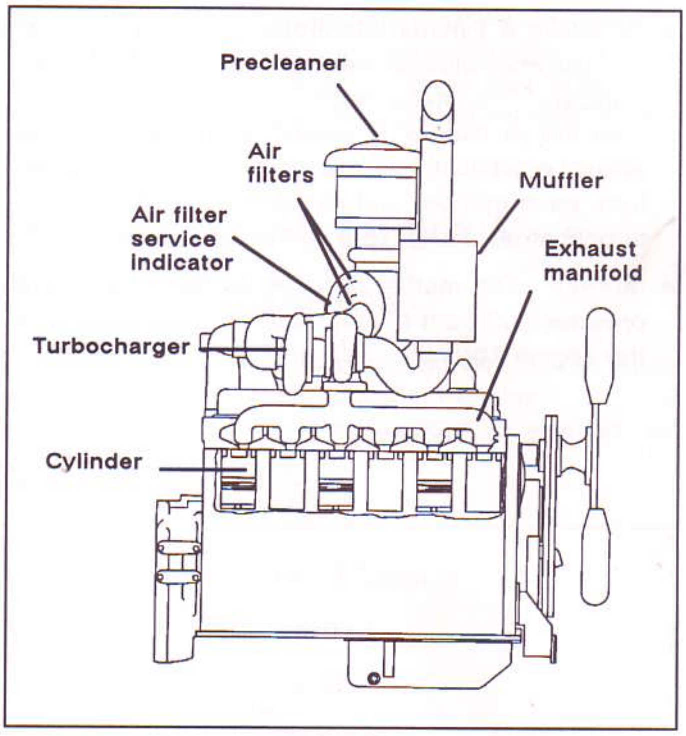
Piston failure due to incorrect fuel injection

When incorrect atomization or fuel injection occurs, fuel is injected into the cylinder in a stream instead of in an atomized state. This happens if an injector is plugged or has a broken tip. Instead of a smooth, complete burning of the fuel, the liquid ignites into a burning stream of fuel, much like a cutting torch. The temperatures get so high and the burning is so concentrated that it can actually cut into the piston. In addition, some of the unburned fuel runs down the liner walls. This washes off the protective oil, reducing lubrication and accelerating ring and liner wear and piston scuffing.

When fuel is not atomized correctly, the combustion process takes longer than normal, leaving unburned fuel in the cylinder. Again, the problem of fuel running down the liner walls occurs. This is typically a fuel system problem and should be handled by the service department. The leading indicators are; excessive black smoke, a lack of power, and fuel contamination of the engine oil.

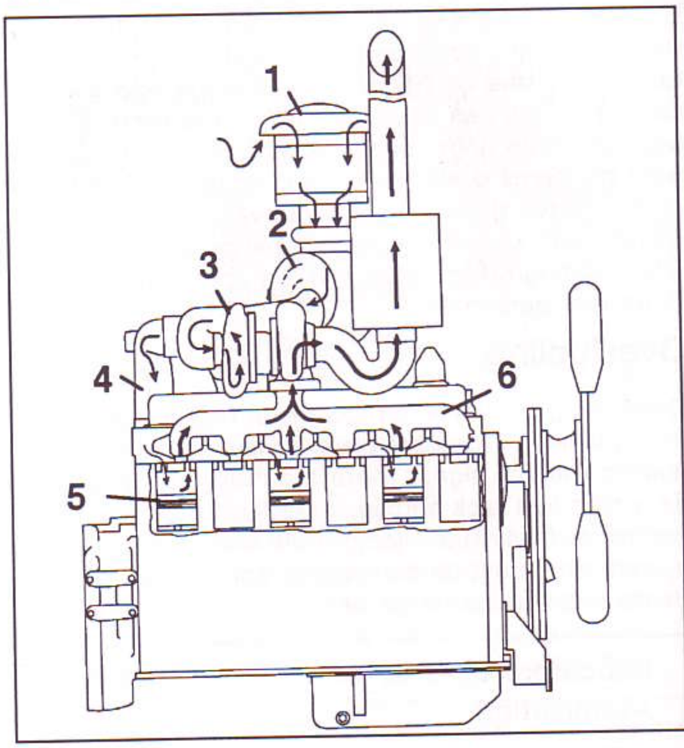
IV. Air Intake & Exhaust System

The air intake system supplies clean air for engine combustion. The exhaust system takes away exhaust gases and heat, and drives the turbocharger. The components that make up the air intake and exhaust system include the following.



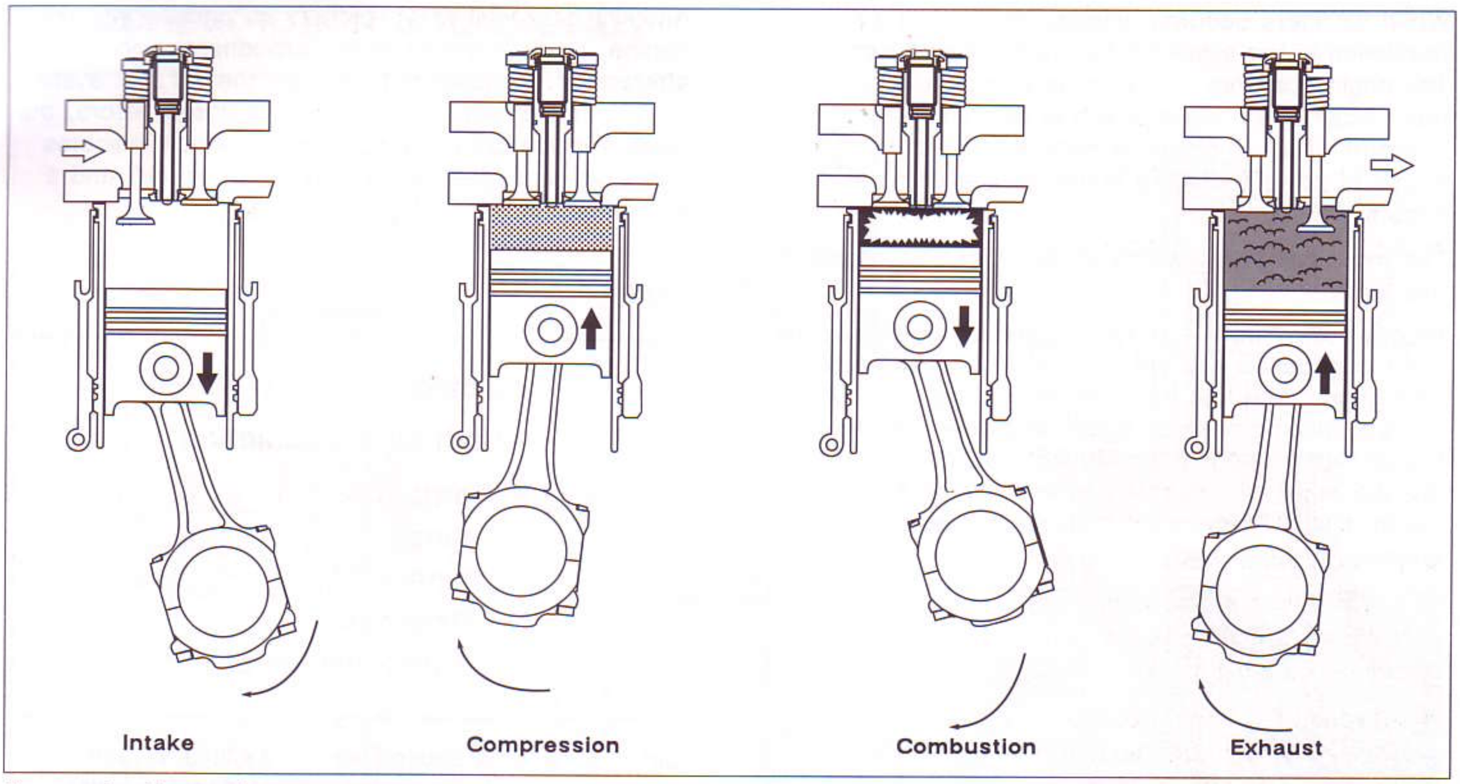
- **Precleaner** – The precleaner removes large particles of dirt and debris.
- **Air Filters** – Usually there are two air filters, a primary and secondary filter. They collect contaminants and prevent dirt from entering the engine.
- **Air Filter Service Indicator** – The indicator monitors restriction through the air filters. It is the most accurate method for determining when to change air filters. Every engine should have one. An interesting fact is that changing filters too often can actually do more harm than good – because dirt can so easily enter the engine during a filter change. This makes the indicator a very useful and important maintenance tool.
- **Turbocharger** – Exhaust gases drive the turbocharger which pumps additional air into the engine allowing more fuel to be burned, thereby increasing the horsepower output.
- **Aftercooler** – The aftercooler cools the air after it leaves the turbocharger but before it enters the engine. This increases the air density, so more air can be packed into each cylinder.
- **Air Intake & Exhaust Manifolds** – The air intake and exhaust manifolds connect directly to the cylinder head(s). The intake manifold distributes clean air from the air filter or turbocharger into each cylinder, while the exhaust manifold collects exhaust gases from each cylinder and directs them to the turbocharger and/or to the muffler.
- **Muffler** – The muffler reduces the sound level and provides sufficient back pressure to the engine, so the engine "breathes" as designed.

How the Air Intake and Exhaust System Works

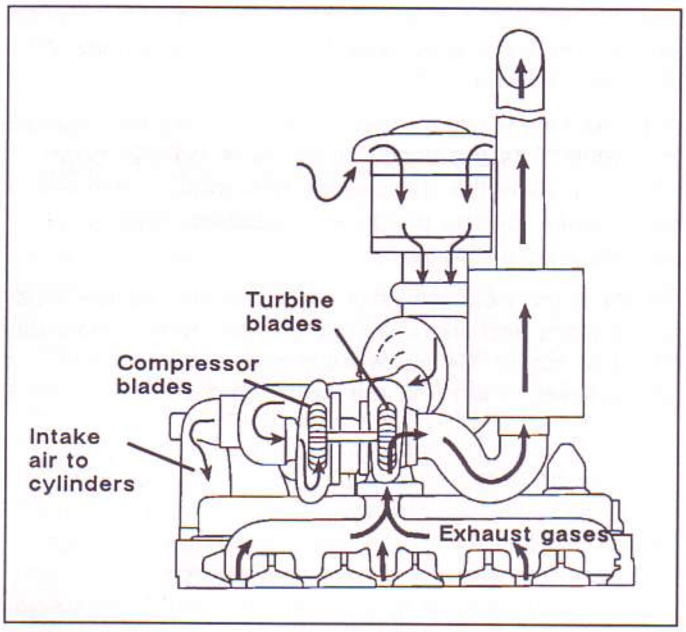


1. Air first enters the system via the precleaner. Here large dirt particles are removed.
2. Then air moves through the primary and secondary air filters for further cleaning.

   On turbocharged engines the spinning of the turbocharger compressor wheel pulls air into the turbocharger.
3. The compressor wheel compresses the air (whic also heats it) and sends it to the aftercooler. The aftercooler reduces the air temperature making it more dense so more air can be packe into the cylinders.
4. The dense compressed air moves from the aftercooler through the air intake manifold and cylinder head(s)
5. past the intake valves into each cylinder combustion chamber. As the intake valves clos and the piston moves up in the cylinder the air compressed further. When the piston is near t top of its stroke, fuel is injected into the combustion chamber. The fuel mixes with the hot, compressed air and ignites. The force of the combustion pushes the piston down on the power stroke.
6. When the piston moves up again it is on the exhaust stroke. The exhaust valves open allow exhaust gases out through the exhaust manifol



The combustion cycle



Turbocharger operation

Exhaust gases flow through the exhaust manifold into the turbine side of the turbocharger to drive the turbine wheel. The turbine wheel is connected by a shaft to the compressor wheel. The compressor wheel pulls air into the system. Exhaust gases after driving the turbine wheel pass out through the muffler and exhaust stack.

On engines without turbochargers air moves directly from the precleaner and air cleaner through the intake manifold into the cylinders. After the combustion cycle, exhaust gases exit through the exhaust manifold and muffler.

Diagnosing Air Intake & Exhaust Problems

The two major problems associated with the air intake and exhaust system that can affect engine performance and life are: not enough air and dirty air.

Not Enough Air

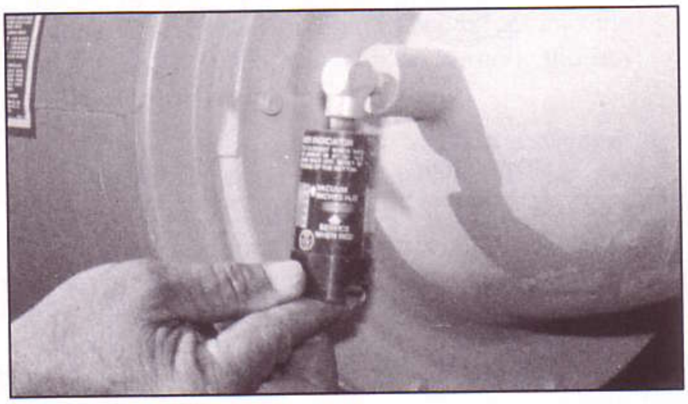
Indicators of Lack of Air

- **Black smoke**
- **Low power**
- **Hard starting**

When air filters become plugged or there is a restriction in the system, the engine is starved for air. The engine can not efficiently or completely burn the fuel. Most often this problem is diagnosed by an operator who complains of excessive black smoke or a loss of power - before actual engine damage occurs.

The most common causes of air restriction include the following.

Plugged Air Filters - Dirty, plugged air filters are the most overlooked and yet the primary cause of air restriction. The first item that should be checked if there is black smoke or a lack of power complaint is the air filter. Remember air filter service indicators are the most accurate way to know when to change the air filters. They should be recommended for all engines, if not already equipped.



The air filter service indicator

Malfunctioning Turbocharger - If turbocharger bearings or seals wear to the point that turbocharger speed is reduced or if the blades contact the housing there will be insufficient air going to the cylinders for complete combustion.

Plugged Aftercooler - Any restriction in the aftercooler will decrease the amount of air into the cylinders.

Exhaust Restriction - A restriction in the exhaust will slow the turbocharger since it is driven by exhaust gases. This will reduce the amount of intake air going into the cylinders and cause a loss of power. Exhaust restrictions can be caused by customized exhaust systems that are incorrectly matched to the engine, damaged mufflers and pipes and other items that restrict air flow.

Anything that inhibits or restricts air coming into the engine, through the air filter, turbocharger or aftercooler, or going out, through the exhaust system, will affect efficient combustion. As noted before, the leading indicators are black smoke, which indicates unburned fuel (due to not enough intake air) and a loss of power.

Dirty air

Indicators of Dirty Air

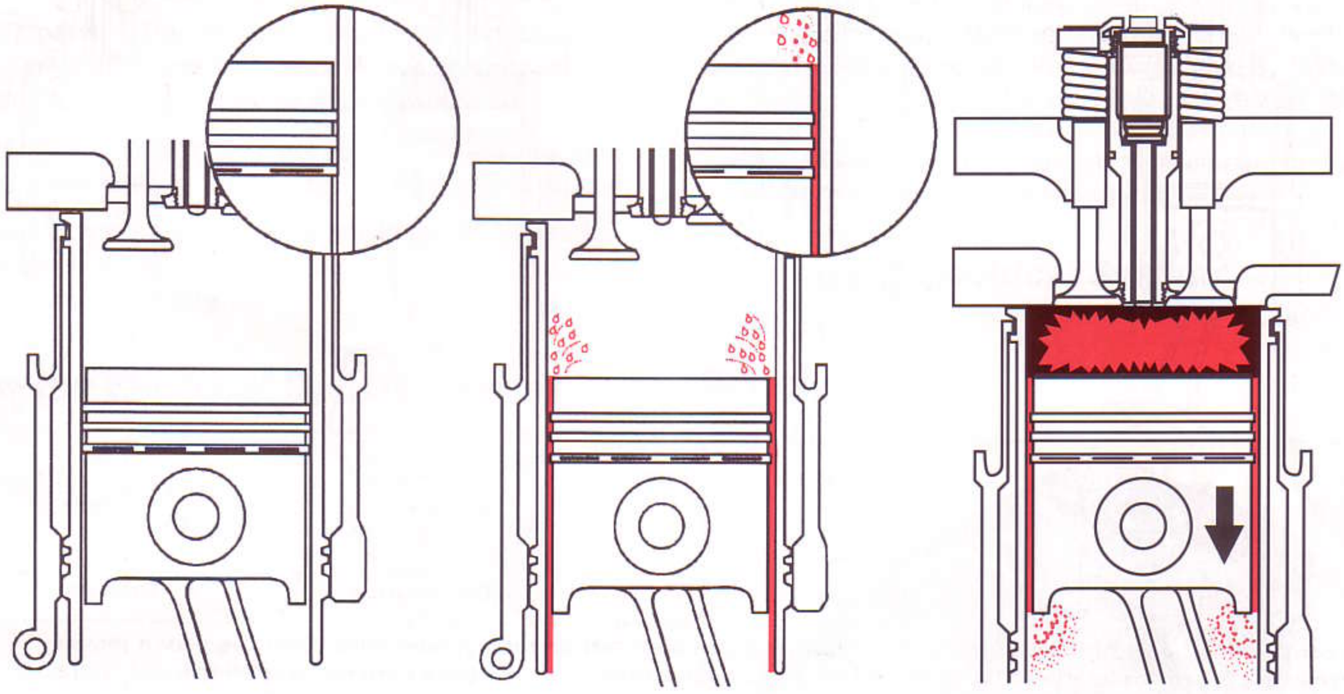
- **High oil consumption**
- **Worn:**
  - **Rings**
  - **Liners**
  - **Bearings**
  - **Turbocharger parts**

Dirt in an engine causes wear. As little as one teaspoon of dirt can cause severe damage and possibly shut the engine down. Common problems that can allow dirt in an engine include a split or smal pin-hole in a hose, a loose hose or pipe connection, or a torn air filter.

Dirt that enters the engine collects on the oily cylinde liner walls. As the piston rings move up and down along the walls the dirt causes fine wear, much like sand paper, on the piston ring grooves, rings and cylinder liner surfaces.

S•O•S is the best indicator of dirt entry. Before wea of the rings and liners will cause blowby and increase oil consumption S•O•S will warn of an increase in silicon levels - alerting the owner to a problem.

Oil Consumption and Blowby



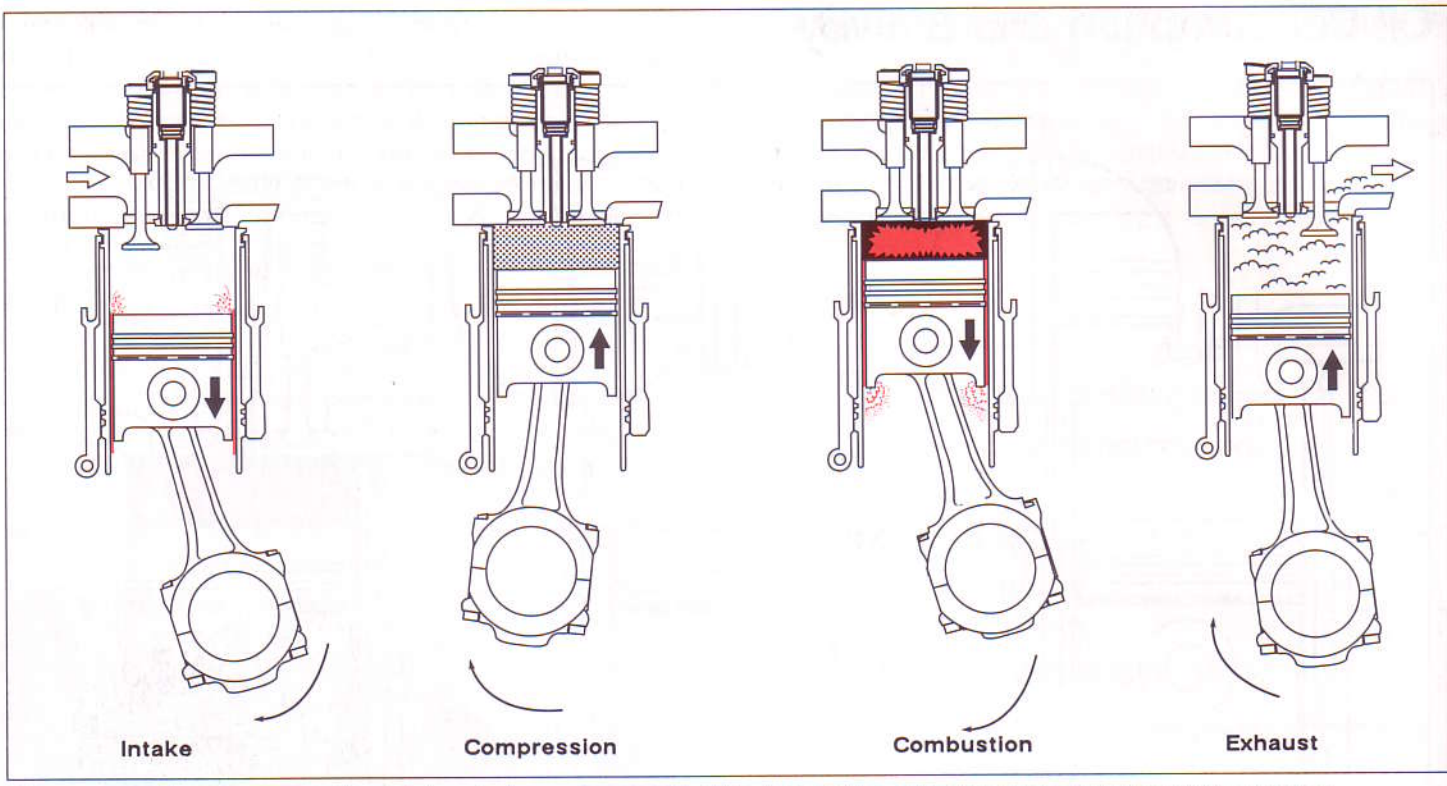
Normal engine operation on the left, ring and liner wear causing increased oil consumption on the right.

Here is a good place to explain oil consumption and blowby. Oil consumption occurs when lubricating oil on the cylinder liner walls is allowed past the piston rings into the combustion chamber or when oil passes into the combustion chamber due to excessive clearance between the valves and valve guides. Normally the rings control the amount and thickness of the oil on the liner wall, but if worn, the increased clearance between the ring and liner allows excessive amounts of oil in the combustion chamber. The oil then burns along with the fuel. As the engine operates, additional amounts of oil are consumed creating the need to continually add oil to the engine.

Blowby occurs when combustion gases travel past the rings and/or valves and valve guides from the combustion chamber into the crankcase. This allows carbon, soot and other contaminants to mix with the oil increasing engine wear.

Other causes of increased oil consumption and blowby include:

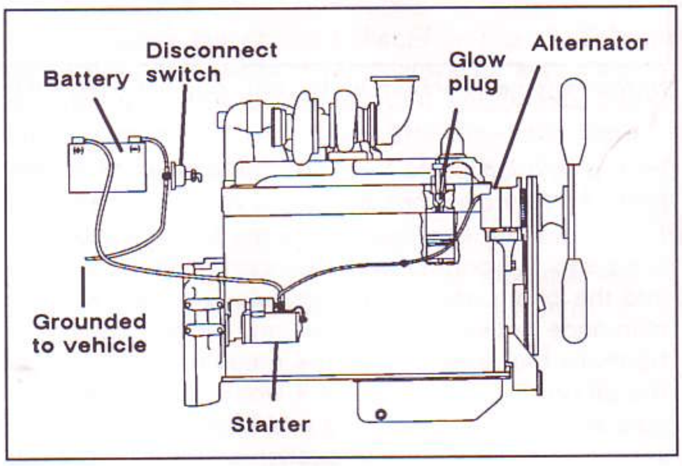
- worn turbocharger bearings and seals
- worn crankshaft seals
- worn oil-lubricated governor seals
- oil leaking into the fuel or cooling systems



Oil consumption occurs on the intake stroke as too much oil is left on the cylinder liner when the piston moves downward. Blowby occurs on the compression and power stroke as gases pass between worn rings and liners.

The terms oil consumption and blowby are often used interchangeably. To assist in diagnosing engine problems, blowby is a more specific term and is easier to measure than increased oil consumption. Blowby can be checked by measuring crankcase pressure with a pressure gauge or by checking blowby volume with a blowby meter. Oil consumption is harder to measure since it depends on good consistent maintenance records - something many customers don't have. Also blowby can be measured at any time. Whereas oil consumption has to be measured over several days or weeks. The important point is oil consumption and blowby both result from engine wear, and the most common type of engine wear is piston ring and liner wear.

V. Electrical System



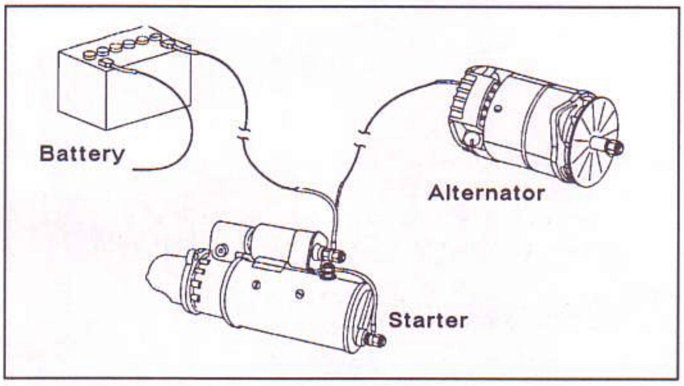
The primary function of a diesel engine's electrical system is to start the engine. The secondary function is to power lights, gauges and vehicle electrical components. (Some of the latest engines in the on-highway truck market also have electronic fuel controls).

It's interesting to note that after cranking a diesel engine, the battery is no longer needed to continue running because there is no ignition system required for combustion, as on a gasoline engine.

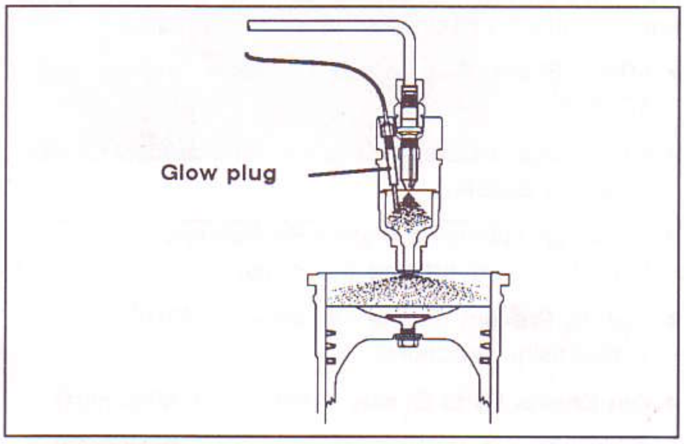
Major Components in the Electrical System

- **Battery** – The battery stores electrical energy.
- **Alternator** – The alternator creates electrical energy to replenish the charge level in the battery. A voltage regulator is inside the alternator.
- **Starter** – The starter motor is powered by electricity from the battery. Its function is to start the engine.
- **Glow plugs** – Glow plugs preheat the air for easier engine starting. They are only found on precombustion engines.

How the Electrical System Works



The battery stores energy and provides the power needed for the electrical starter to crank the engine. As electrical energy is used out of the battery it has to be replenished. The alternator develops electrical energy during machine operation to replenish the battery.

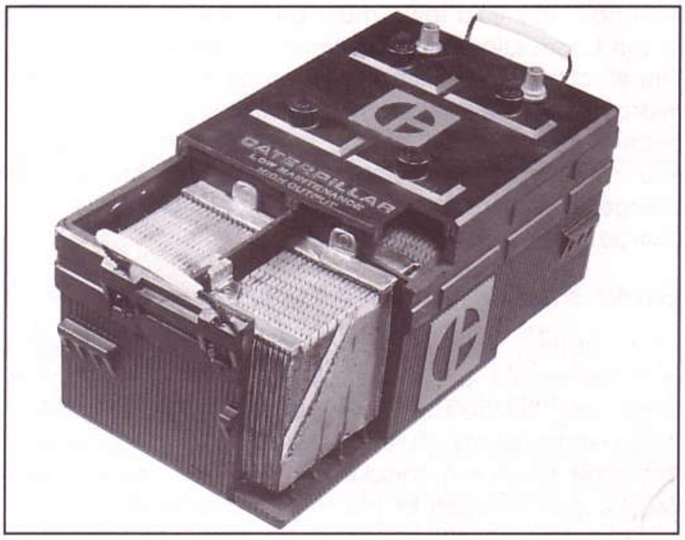


Glow plug used for starting precombustion engines

For quicker and easier engine starts, precombustion engines use electrical glow plugs to warm and preheat the air in the precombustion chamber before cranking. They heat for approximately one minute. And even at 60°F (15.5°C) temperatures it's a good practice to heat the glow plugs for a short time. If not preheated, the extreme temperature change, from ambient to combustion temperature, can cause the tips of the glow plugs to break off. Basically it's better to heat them up gradually with electricity than to shock them with combustion heat.

Diagnosing Electrical System Problems

Battery



A majority of electrical system problems are related to the battery and most commonly result from a lack of maintenance. Battery maintenance is very simple – keep the battery filled, clean, and clamped down correctly.

If not secured correctly with the clamps, the battery will bounce around during machine operation causing the internal plates and connections to crack and break resulting in a battery failure. Extreme jarring can even cause the case to crack, allowing the fluid to leak.

Battery terminals and connections should be clean and corrosion-free. On other than maintenance-free batteries, the fluid level must be maintained according to the Lubrication and Maintenance recommendations. The electrolyte concentration can be checked with an hydrometer. This tells how much charge is in the battery. If a "dead" battery is recharged overnight and in the morning still shows only a low charge or no charge at all, the battery will no longer accept a charge and must be replaced.

Glow Plugs

Hard starting, cranking a long time or running rough until the engine is warmed up are signs that the glow plugs may not be functioning correctly. Each glow plug can be easily checked with an electrical meter. The glow plugs are checked during tune ups and as a regular part of each of the engine overhauls.

Alternator & Voltage Regulator

Once the engine is running, the alternator serves as the electrical power source to run lights, gauges, EMS panels, and electrical components, plus replenish the charge in the battery. It is belt driven off the crankshaft.

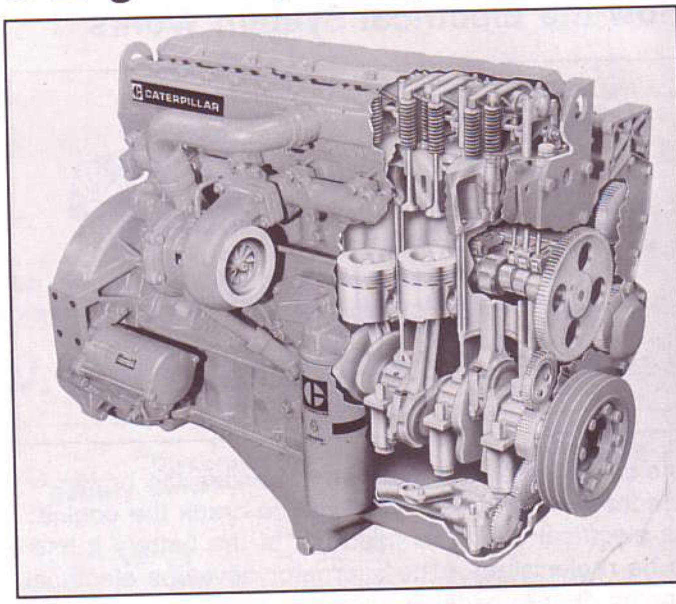
Inside the alternator is a voltage regulator that limits the voltage output to the battery. This prevents overcharging.

If a problem develops with the charging system an alternator light in the cab will go "on". This could signal the alternator is not supplying an adequate charge; or a wire is not connected correctly. If not corrected, the electrical energy will drain out of the battery until no more charge remains.

Slow Cranking Speed

Diesel engines require sufficient cranking speed to develop the high compression pressures needed to ignite the fuel. If the cranking speed is slow the engine will be hard to start. Before calling the service department check the battery and all connections. If the problem is still not identified a serviceman can check the starter and measure the cranking rpm of the engine. The starter or battery may need repair or replacement.

Other Material on Cat Engines & Engine Repair Options



For more information on Cat Engines and Cat Engine Repair options check the following materials.

- ERIK - Engine Repair Indicator Kit - Part number 4C3502
- Introduction to Diesel Engines - TECB6005 (Training Bulletin)
- Guide for Managing Engine Performance - PEDP7101 (Advertising brochure)
- How to Prevent Engine Failure - PEDP6101 (Advertising brochure)
- Cat Engine Parts Quality - PELP7901 (Flipchart)
- Engine Repair Options "Decisions" - PEVN6020 (Videotape)
- Scheduled Oil Sampling S•O•S - PEDP7105 (Advertising brochure)

- Air Filter Service Indicator - PEHP9013 (Advertising brochure)
- Oil and Your Engine - SEBD0640 (Technical Publication)
- Coolant and Your Engine - SEBD0970 (Technical Publication)
- Fuel and Your Engine - SEBD0717 (Technical Publication)
- Know Your Cooling System - SEBD0518 (Technical Publication)
- Caterpillar's Machine Lubrication Recommendations - SEBU6250 - (Technical Publication)

There are many other materials available, check the Marketing Training Materials Catalog (TECM0050) and Product Support Promotion Materials Catalog (PEGP9800) for complete listings. (Your dealership Promotion and/or Training Manager have these catalogs available.)

Conclusion

You now have a good understanding of how diesel engines work, how they wear and the common warning signs of problems.

Use this knowledge to help your customers:

- develop correct preventative maintenance practices
- choose appropriate inspection programs
- select the best repair options for their specific situation

And, as a last note, remember to always demonstrate and reinforce with customers that your dealership's capabilities and Cat products offer the best value available.

Index